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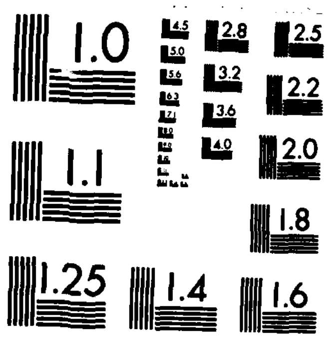

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NSWC TR 83-401

THE EFFECT OF A GLOBAL POSITIONING SYSTEM (GPS) RECEIVER MEASUREMENT ERROR ON GRAVITY ANOMALY SURVEY ACCURACY

BY ALAN G. EVANS

STRATEGIC SYSTEMS DEPARTMENT

DECEMBER 1983

NAVAL SURFACE WEAPONS CENTER

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report determines the contribution of a Global Positioning System (GPS) receiver's measurement error to the accuracy of a gravity anomaly survey. These error contributions are determined for several survey vehicle velocities. keywords include:

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FOREWORD

This report investigates the application of the currently available GEOSTAR Global Positioning System receiver to determine the vertical reference for gravity anomaly surveys.

This report was reviewed by J. N. Blanton and R. W. Hill, Head, Space Flight Sciences Branch.

Approved by:

Thomas A. Clare

THOMAS A. CLARE, Head
Strategic Systems Department

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The author also wishes to thank those who contributed to his background in the gravity area: T. Alexander of NSWC; and B. Zondek, C. Cohen, and O. Schultz, all now retired from NSWC.

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INTRODUCTION

Gravimeters are currently being used on shipboard surveys to measure the earth's gravitational field. The gravimeter measures vertical accelerations due to nongravitational forces acting on the vehicle. Since mean sea level offers an excellent vertical reference and the ship is moving at a low velocity, these accelerations are averaged over a time interval to produce a value very nearly equal to the negative of the gravitational acceleration magnitude. For ships moving with a speed of about 10 kn, the error due to this averaging out of vertical motion is estimated to be a few tenths of a mgal or less (Reference 1). This is small when compared to overall shipboard survey accuracy of about 2 mgal (Reference 1).

For a higher velocity survey vehicle (e.g., an airplane), the averaging time becomes much smaller and is the limit factor for survey accuracy (Reference 2). It becomes necessary to use an external vertical reference. Here, the gravimeter data are subtracted from the vertical reference and then estimated. Up to now, sufficiently accurate vertical referencing has been difficult to obtain, especially over land (Reference 2).

This report investigates the use of a Global Positioning System (GPS) receiver for vertical referencing. (See Reference 3 for GPS background.) This investigation is motivated by recent advances in GPS receiver capability and, specifically, the development of the GEOSTAR* receiver (References 4 and 5). This receiver tracks up to four satellites simultaneously and offers the potential for very accurate vertical measurements. Simulated and actual measurement accuracies of the GEOSTAR are given in the next section.

The purpose of this study is to determine if the currently available GPS receivers, specifically the GEOSTAR receivers, are sufficiently accurate to be used for vertical referencing in gravity surveys. Only the error in vertical referencing due to the receiver itself is used in the study. Consequently, it is assumed that all values used are known perfectly except for the receiver phase measurement noise. This assumption enables values of nongravitational vertical position, velocity, or acceleration determined from the gravimeter to be subtracted directly from corresponding GPS determined values. The residuals of these subtractions are due only to the gravity effect and measurement noise of the receiver. Therefore, the particular vehicle motion does not need to be modeled statistically. Instead, only the gravity anomalies and receiver measurement noise need to be statistically modeled. The remaining accuracy analysis assumptions, the statistical model for the gravity

*Texas Instruments, Inc., is designing and building the GEOSTAR receiver under contract to the Applied Research Laboratories (ARL). NSWC is developing the receiver's control and navigation software. DMA National Oceanic & Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS) are funding the development.

anomalies, and the relationships for the optimum smoothing filter and the corresponding mean square estimation error are discussed herein.

RECEIVER MEASUREMENT ACCURACY

The GEOSTAR receiver was designed to make very precise phase measurements of the GPS satellite transmitted signals. Simulations have been performed at Texas Instruments (Reference 6) to predict the expected phase measurement accuracy for several dynamic environments. These values are listed in Table 1 for stationary, low dynamic (boat or jeep), and medium dynamic (helicopter or airplane) cases. For all of these cases, the maximum expected receiver phase measurement error standard deviation is about 1 cm. These values were obtained using a simulation model and do not include all real world effects (e.g., vehicle vibrations). A phase measurement is equivalent to the range to the satellite with the addition of an unknown bias. However, since derivatives or changes in range are of interest, these bias values are unimportant.

TABLE 1. EXPECTED GEOSTAR MEASUREMENT ACCURACY*

Case	Maximum Velocity (m/s)	Phase Measurement Error (m)	Vertical** Position Error (m)
Stationary	0	0.0015	0.003
Low Dynamic (Boat or Jeep)	25	0.003-0.005	0.006-010
Medium Dynamic (Helicopter or Airplane)	200	0.003-0.01	0.016-0.02

*Values quoted for accuracy are theoretical instrumentation values. Subsequent hardware tests have verified that these values are real within a factor of two or three.

**RMS Vertical Dilution of Precision (VDOP) = 2

More specifically, the vertical accelerations are to be estimated from the receiver biased range measurements. The accuracy with which the vertical component can be computed depends on the number of satellites in view and their relative location with respect to the receiver antenna. The decrease in accuracy due to the locations of the satellites in view is called Vertical Dilution of Precision (VDOP). A value of VDOP = 2, chosen from Reference 3, is the 50th percentile value and close to the root mean square value. This value is based on a range error budget of 3.6 to 6.3 m, a 24-satellite baseline constellation, and a five-degree satellite mask angle. Note that although the assumed constellation of Reference 3 is not the

currently planned 18-satellite/6-plane constellation, the chosen value of VDOP is still thought to be reasonable. The GEOSTAR receiver also measures pseudorange. It is expected that the resulting range measurements, after atmospheric corrections, would be well within the above assumed range error budget. Multiplication of the VDOP value by the range instrumentation accuracy produced the estimated vertical measurement accuracy. The vertical measurement accuracies are also given in Table 1.

Measured average velocity values of the prototype GEOSTAR are presented in Reference 4. These values are taken from a stationary antenna, but the tracking filter parameters were not set for the stationary case. The phase measurements were differenced at 4-s intervals to form the average velocity values. This was done for the four GPS satellites available on both the L_1 and L_2 channels. The average standard deviation of the relative velocity measurement error computed from these data was 0.003 m/s. This value is over a relatively short data interval of 9 min, but it also includes all other measurement errors in addition to the receiver measurement errors. A corresponding vertical velocity error standard deviation is 0.006 m/s.

The above values of vertical position (with a bias) and vertical velocity measurement accuracies indicate the current capabilities of a GPS receiver. These values will be used later in the accuracy analysis to determine gravity anomaly measurement accuracy.

ACCURACY ANALYSIS ASSUMPTIONS AND DEFINITIONS

The following assumptions are made for the accuracy analysis:

1. The survey vehicle is on, or near, the earth's surface and is traveling in a constant direction at a constant speed. These are reasonable assumptions, since survey vehicles would generally travel this way.

2. This analysis is to determine if the receiver measurements are sufficiently accurate for a gravity anomaly survey. All other values are assumed to be known perfectly. The receiver vertical measurement error is statistically modeled as white noise (i.e., constant power over all frequencies).

3. The GPS vertical direction is normal to the earth's ellipsoid. The gravimeter vertical direction is normal to the earth's geoid. This small angular difference, normally about a few arc seconds, is assumed to have a negligible effect on the magnitudes of the acceleration values. In other words, the magnitude of the acceleration in one vertical direction is very nearly equal to the magnitude of the component of acceleration in the other vertical direction. Also, perfect modeling of the vertical coupling between the gravimeter and the GPS antenna is assumed.

4. The data are assumed to be sampled sufficiently fast so that continuous signal analysis procedures can be used. The sampling interval chosen for the survey gravity data, discussed in the next section, is 1 nmi (Reference 7). The Nyquest frequency (the reciprocal of twice this sampling interval)

represents the highest frequency of interest in the gravity data (Reference 8). A sampling interval of one sample/s in a vehicle at the maximum velocity of the study, 100 m/s, would have a cutoff frequency of 18 times the practical gravity cutoff frequency. The GEOSTAR receiver is capable of taking measurements of up to 25 times/s. Therefore, the sampling rate appears to be sufficient for this assumption.

5. The gravity anomalies can be statistically modeled. Here, stationarity and other assumptions (Reference 9) are required. The statistical model chosen is described later in this report.

The following definitions are used in the analysis:

$g(t)$ = true gravity magnitude

= (total-vertical acceleration determined from GPS)-(nongravitational vertical accelerations measured by the gravimeter)

$\Delta g(t)$ = gravity anomaly

= $g(t)$-(ellipsoidal model gravity magnitude)

$f(t)$ = vertical position due to $g(t)$ (with bias)
$= \iint \Delta g(\lambda)\, d\lambda\, dt$

$z(t)$ = receiver vertical positioning measurement (white) noise

GRAVITY ANOMALY STATISTICAL MODEL

The statistical model chosen for the gravity anomalies is given by the auto-orrelation function (Reference 9)

$$\phi_{\Delta g \Delta g}(\tau) = \sigma^2_{\Delta g} \left(1 + \beta\, |\tau| - \frac{\beta^2}{2} |\tau|^2\right) \exp\left(-\beta\, |\tau|\right) \qquad (1)$$

here

$\beta = v/D$

v = constant speed of the survey vehicle

D = correlation length

$\sigma_{\Delta g}$ = gravity anomaly standard deviation

ote that since the vehicle is moving in a constant direction and at a constant peed, the radial change in the distance parameter of the autocorrelation function f Reference 9 is converted to a change in the time parameter. This analysis is one for several values of vehicle speeds. A value of $\sigma\Delta g = 35.0$ mgal is chosen as worldwide value for the gravity anomaly standard deviation (Reference 10). A alue of the correlation length $D = 2.76\times10^4$ m is chosen, since it matches the higher

frequency gravity data very well (Reference 11) and it is one of the values recommended in Reference 9. This autocorrelation function is derived from a third-order Markov autocorrelation function of the undulation. A physically reasonable autocorrelation function for the vertical deflections that makes the statistical gravity models self-consistent can also be derived from the undulation model (Reference 9).

The corresponding gravity anomaly Power Spectral Density (PSD), found by taking Fourier Transform of Equation (1), is

$$\Phi_{\Delta g \Delta g}(\omega) = 2\ \sigma\Delta g^2 \beta^3 \left[\frac{\beta^2 + 5\ \omega^2}{(\beta^2 + \omega^2)^3}\right] \qquad (2)$$

where ω is the frequency in rad/s.

Here, the PSD is given in units of $(\mathrm{mgal})^2/\mathrm{rad/s}$. Figure 1 compares this PSD, after conversion of both ordinate and abscissa units, with a representative numerically determined PSD. The numerically determined PSD is obtained (Reference 7) from a 551-nmi gravity anomaly data tract. Figure 1 indicates that the PSD model is a reasonable representation of the statistics of the gravity anomaly.

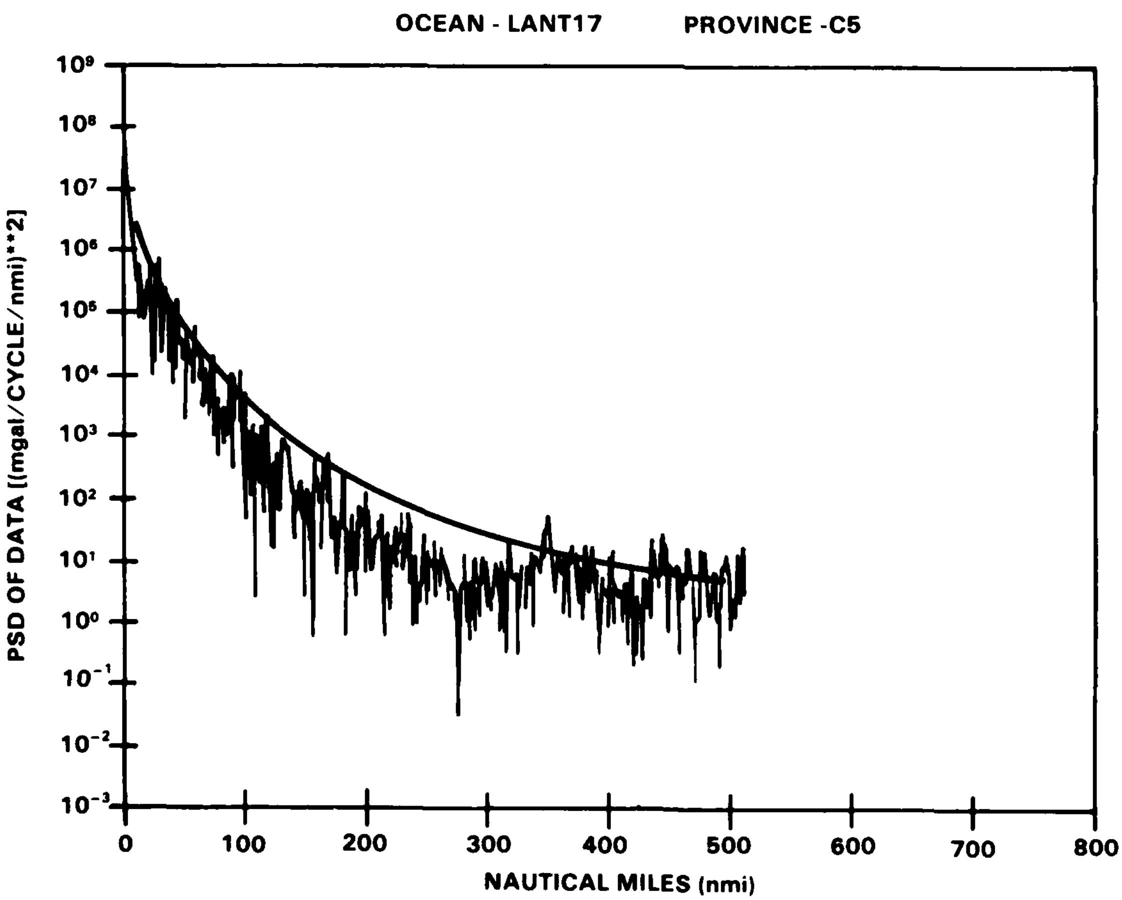

FIGURE 1. MODEL AND REPRESENTATIVE GRAVITY ANOMALY POWER SPECTRAL DENSITY

OPTIMUM SMOOTHING FILTER

The problem can be stated as follows: Given the measured vertical position due $\Delta g(t)$,

$$z(t) = f(t) + \eta(t) \tag{3}$$

:h $f(t)$ and $\eta(t)$ as defined above, optimally estimate

$$\Delta g(t) = f''(t) \tag{4}$$

:h that the mean square error of the estimate is minimized.

The measurement noise is assumed to be white. Therefore,

$$\Phi\eta\eta(\omega) = n^2 \tag{5}$$

:re n is a constant parameter of the analysis. From Equation (4),

$$\Phi_{ff}(\omega) = \Phi_{\Delta g \Delta g}(\omega)/\omega^4 \tag{6}$$

ıce the measurement is completely uncorrelated to the gravity anomalies,

$$\Phi_{f\eta}(\omega) = \Phi_{\eta\varepsilon}(\omega) = 0 \tag{7}$$

The optimum smoothing filter is given by (see Reference 12 and 13 for details)

$$H(j\omega) = \frac{\Phi_{\Delta gz}(\omega)}{\Phi_{zz}(\omega)} \tag{8}$$

:re

$$\Phi_{\Delta gz}(\omega) = \omega^2 \ \Phi_{fz}(\omega)$$

$$\Phi_{fz}(\omega) = \Phi_{ff}(\omega) + \Phi_{f\eta}(\omega)$$

$$\Phi_{zz}(\omega) = \Phi_{ff}(\omega) + \Phi_{\eta\eta}(\omega)$$

.sequently,

$$\Phi_{\Delta gz}(\omega) = \frac{2\sigma_{\Delta g}^{2}\beta^3}{\omega^2} \left[\frac{\beta^2 + 5\omega^2}{(\beta^2 + \omega^2)^3}\right] \tag{9}$$

$$\Phi_{zz}(\omega) = \frac{2 \ \sigma_{\Delta g} \ \beta^3}{\omega^4} \left[\frac{\beta^2 + 5\omega^2}{(\beta^2 + \omega^2)^3}\right] + n^2 \tag{10}$$

:itution of Equations (9) and (10) into (8) gives

$$H(j\omega) = \frac{(\beta^2 + 5\omega^2)}{\beta^2 + 5\omega^2 + K\omega^4\ (\beta^2 + \omega^2)^3} \tag{11}$$

:

$$K = \frac{n^2}{2\sigma_{\Delta g}{}^2\beta^3}$$

:orresponding mean square estimation error of this filter is given by (Refer-
; 12 and 13)

$$\sigma_e^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left[\Phi_{\Delta g \Delta g}(\omega) - w^2\Phi_{ff}(-\omega)H(j\omega)\right] d\omega \tag{12}$$

:itution of Equations (2), (6), and (11) into Equation (12) produces

$$\sigma_e^2 = \sigma_{\Delta g}^2 \left[1 - \frac{1}{\pi} \int_0^{\infty} \frac{2\ \beta^3\ (\beta^2 + 5\ \omega^2)^2\ d\omega}{(\beta^2 + \omega^2)^3 \left[\beta^2 + 5\omega^2 + K\omega^4\ (\beta^2 + \omega^2)^3\right]}\right] \tag{13}$$

RESULTS

The parameter values previously defined are substituted into Equation (13) and :ically integrated for different values of noise standard deviations, n, and :le speeds, v. The results are shown in Figure 2. The estimation error is :ed for vehicle speeds of 1 (about 2 kn), 10, 20, and 100 m/s. As the vehicle's l increases, the averaging time decreases and the estimation error increases. ;ravity anomaly estimation error due to receiver measurement noise is less than ıl for vertical measurement errors of 5 cm or less and vehicle speeds up to 100 From the GEOSTAR receiver data described in the RECEIVER MEASUREMENT ACCURACY .on, this seems to be within the receiver's measurement accuracy capabilities.

A similar plot is shown in Figure 3. This is the result of repeating the above ŕsis with measurements in vertical velocity instead of vertical position. The :sponding measurement noise is now in units of m/s. Here, the results are not : as good. However, if it could be assumed that the noise on the velocity mea- ıents of the receiver as given in Reference 4 is white, the error in estimating .ty anomalies due to this measurement noise would be less than 2 mgal for :le velocities of 100 m/s or less.

CONCLUSION

The results shown in Figures 2 and 3 indicate that the GEOSTAR receiver itself ld be capable of making sufficiently accurate measurements to be used as a .cal reference on gravity anomaly survey vehicles moving at speeds of 100 m/s kn) and less. Other vertical referencing error sources will be discussed.

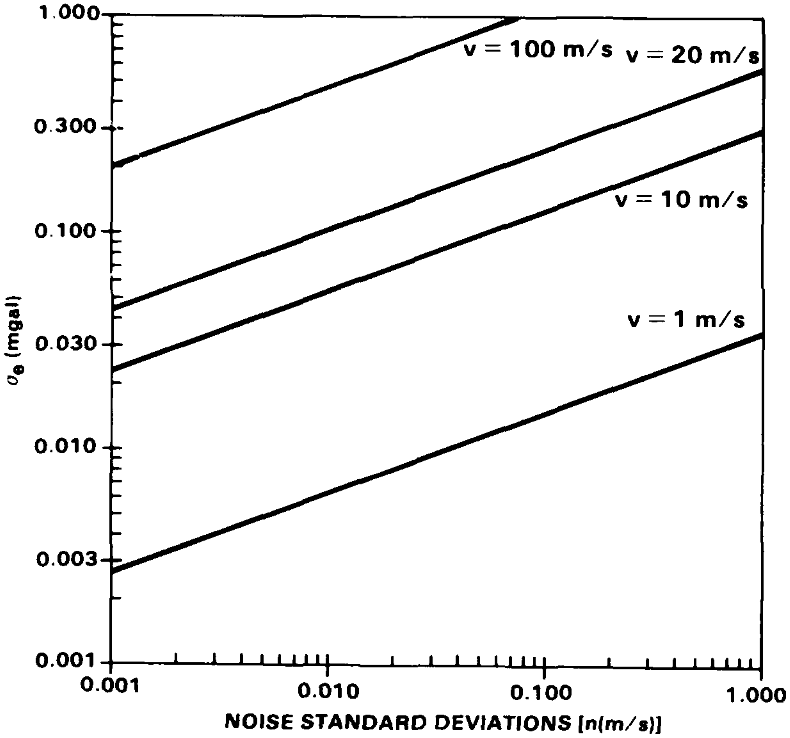

FIGURE 2. GRAVITY ANOMALY ESTIMATION ERROR VS VERTICAL POSITION MEASUREMENT NOISE

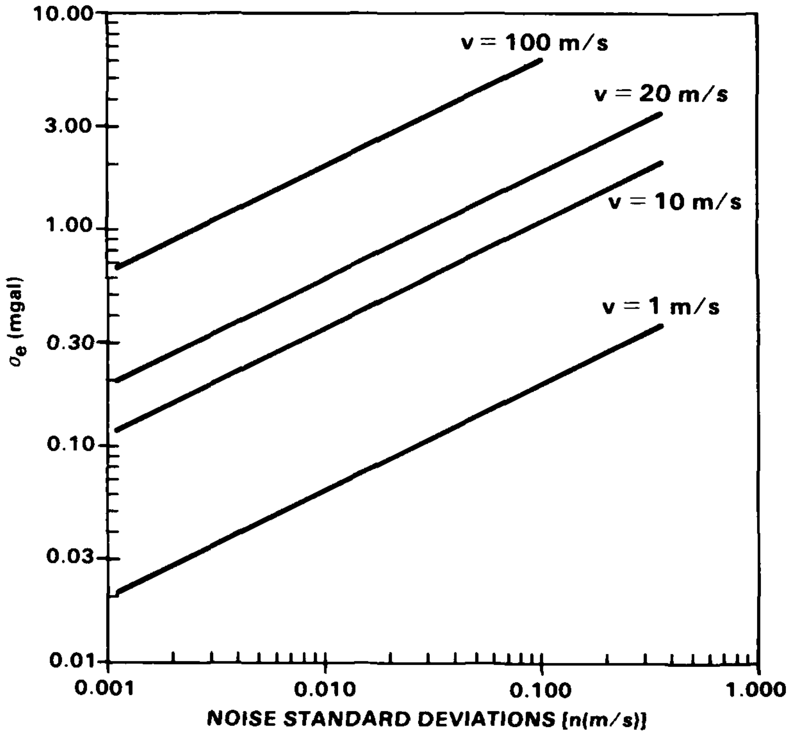

FIGURE 3. GRAVITY ANOMALY ESTIMATION ERROR VS VERTICAL VELOCITY MEASUREMENT NOISE

The GPS satellite errors contributing to survey inaccuracy include orbit error, antenna vibration, and clock error. The effect of these errors could be reduced by having additional receivers on the ground at precisely known positions determined from GPS and within several hundred miles of the survey vehicle.

Two important GPS measurement error contributors are the receiver clock error and the atmospheric correction errors. On the short term, these errors seem to be sufficiently small. Over time spans of a few seconds, the change in the clock error and the change in the atmospheric error are very small. However, the longer term changes may significantly affect survey accuracy. Also, since inertial forces introduce fluctuations in the clock, acceleration compensation in the oscillator and special shock mounting appear to be necessary (Reference 14).

In addition to the above error sources, accurate compensation for movement of the electrical phase center within the antenna must be accomplished. Also, the coupling between the GPS antenna and the gravimeter must be modeled very well. The errors of currently available gravimeters, once the biases are removed, appear to be small compared with other errors in the survey procedure (Reference 1).

In addition to determining vertical acceleration, the GPS receiver is capable of determining position. Importantly, horizontal velocity measurements can also be obtained. The Horizontal Dilution of Precision (HDOP) is slightly better than the VDOP previously discussed. These measurements should reduce the effect of the coriolis error, which is currently the limiting factor for accuracy of the shipboard surveys (Reference 1).

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